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(54) **THERMOPLASTIC COMPOSITE TUBULAR STRUCTURES AND METHODS OF FABRICATING THE SAME**

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USPC 156/173, 187, 189, 184, 180, 218, 148, 156/393; 138/123

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,946,526 A * 8/1990 Petty-Galis et al. 156/155
4,983,240 A * 1/1991 Orkin et al. 156/148

(Continued)

FOREIGN PATENT DOCUMENTS

DE 102011011577 A1 4/2012
WO 92/12847 A1 8/1992
WO 92/20503 A1 11/1992

OTHER PUBLICATIONS

PCT Notification of Transmittal of The International Search Report and The Written Opinion of the International Searching Authority for PCT Counterpart International Application No. PCT/US2013/058538, Applicant The Boeing Company, Mailed Dec. 5, 2013, 11 pages.

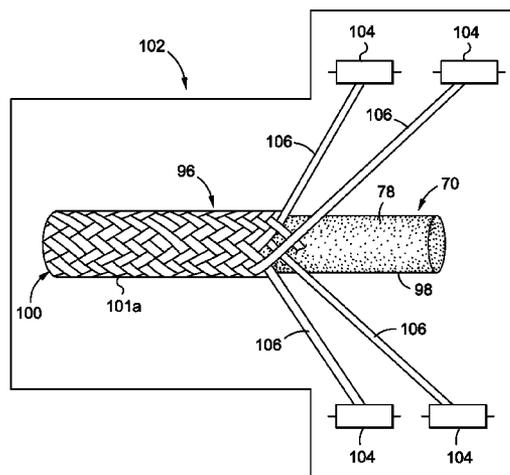
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(57) **ABSTRACT**

A method of fabricating a thermoplastic composite tubular structure provides a mandrel of a soluble, expandable material. The method overbraids the mandrel with a continuous fiber thermoplastic composite material to form an overbraided mandrel. The method installs the overbraided mandrel into a matched tooling assembly. The method heats in a heating apparatus the matched tooling assembly with the installed overbraided mandrel at a specified heating profile in order to consolidate the thermoplastic composite material and form a thermoplastic composite tubular structure. The method cools the matched tooling assembly with the formed thermoplastic composite tubular structure at a specified cooling profile. The method removes the formed thermoplastic composite tubular structure from the matched tooling assembly. The method solubilizes the mandrel to permanently remove the mandrel from the formed thermoplastic composite tubular structure.

15 Claims, 10 Drawing Sheets



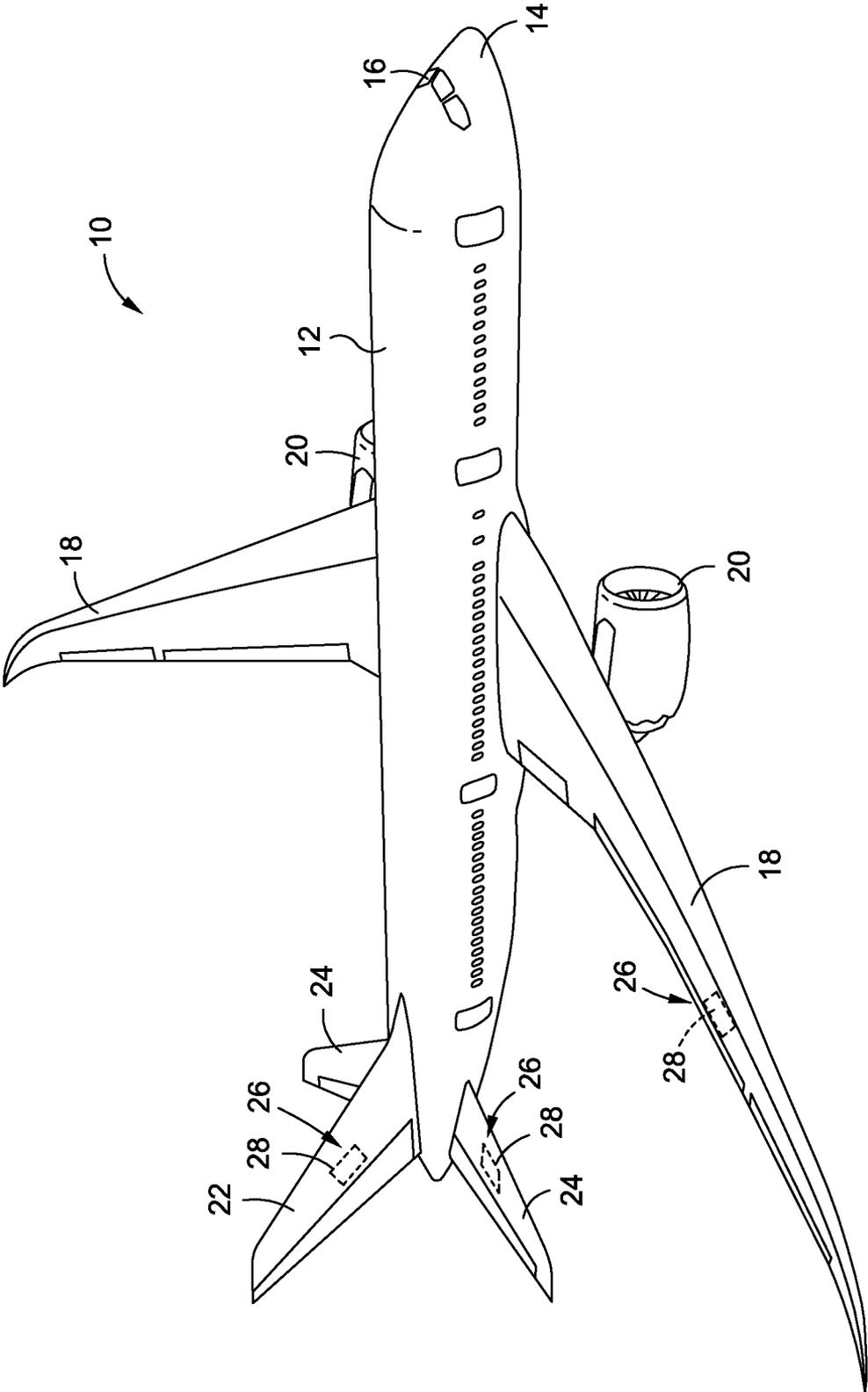


FIG. 1

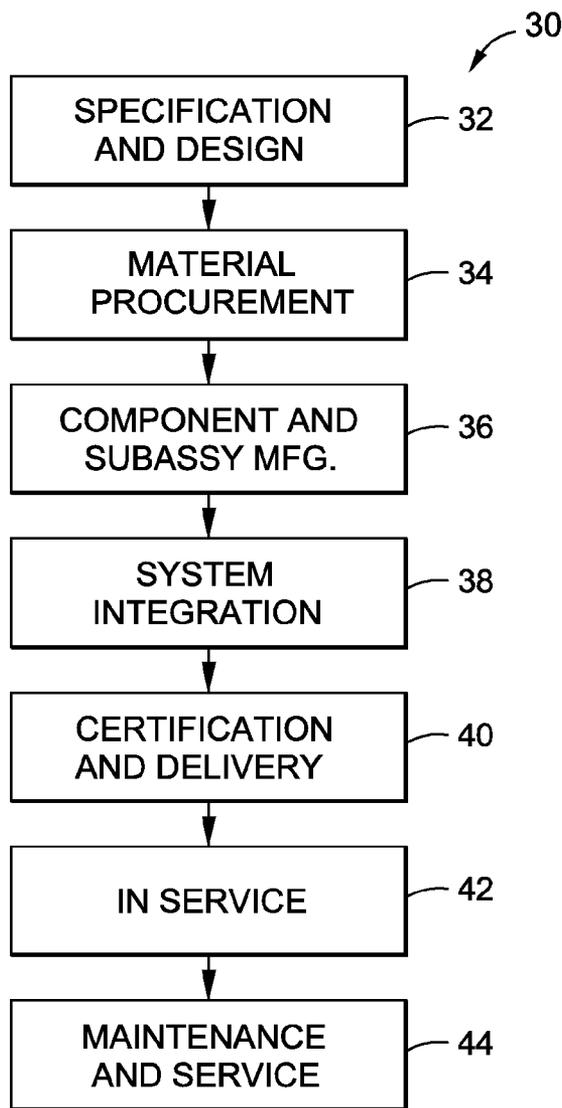


FIG. 2

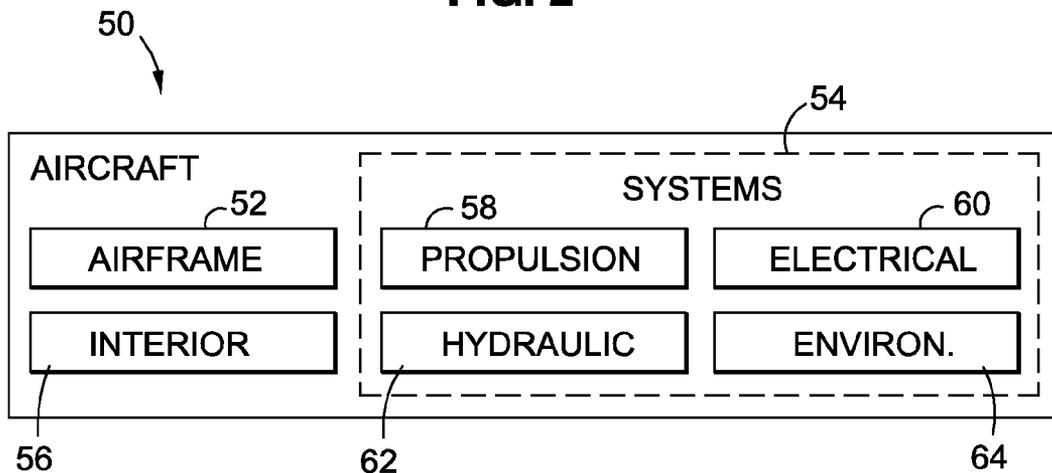


FIG. 3

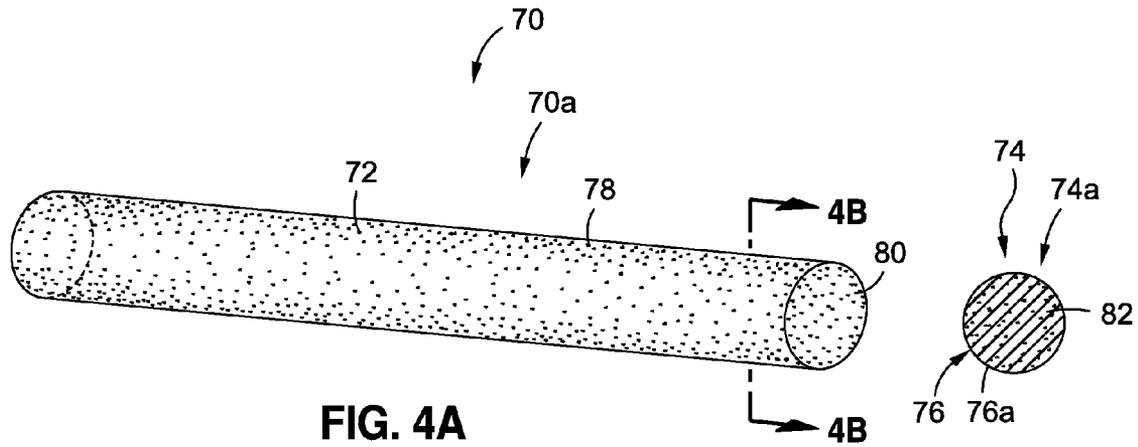


FIG. 4A

FIG. 4B

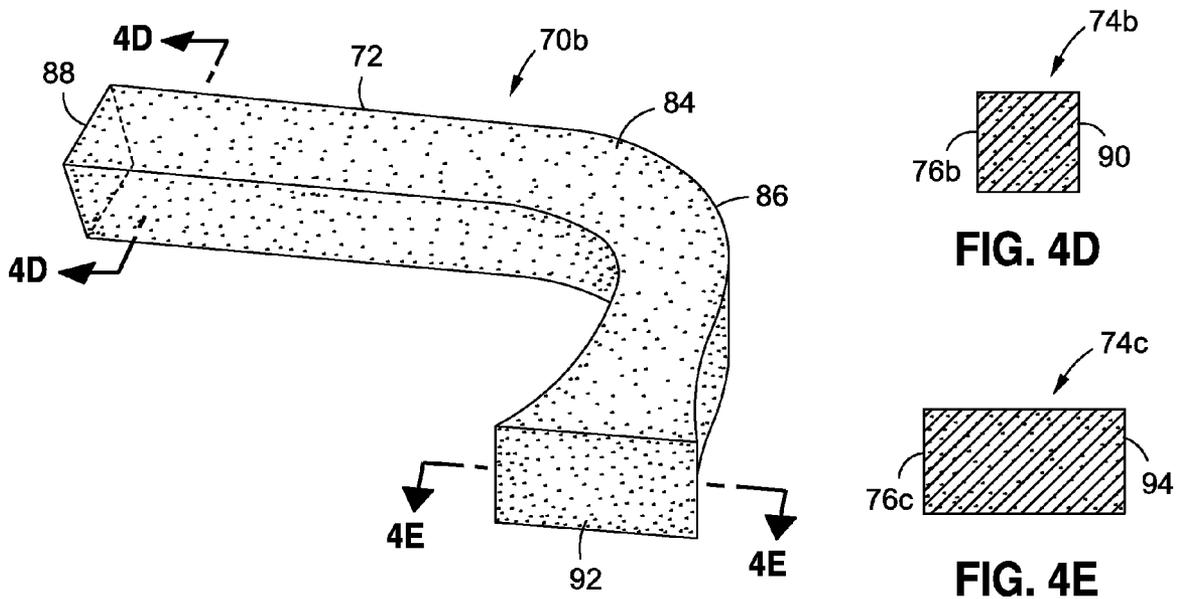


FIG. 4C

FIG. 4D

FIG. 4E

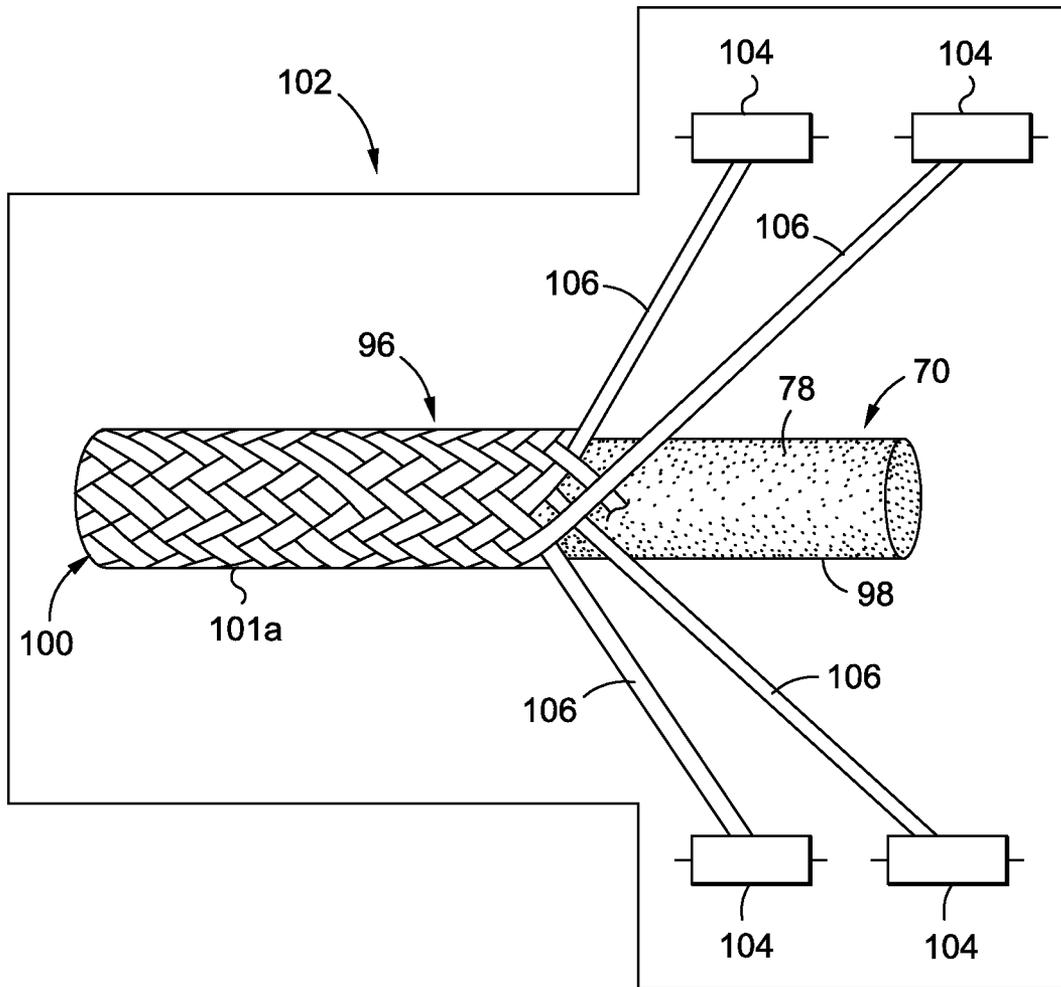


FIG. 5A

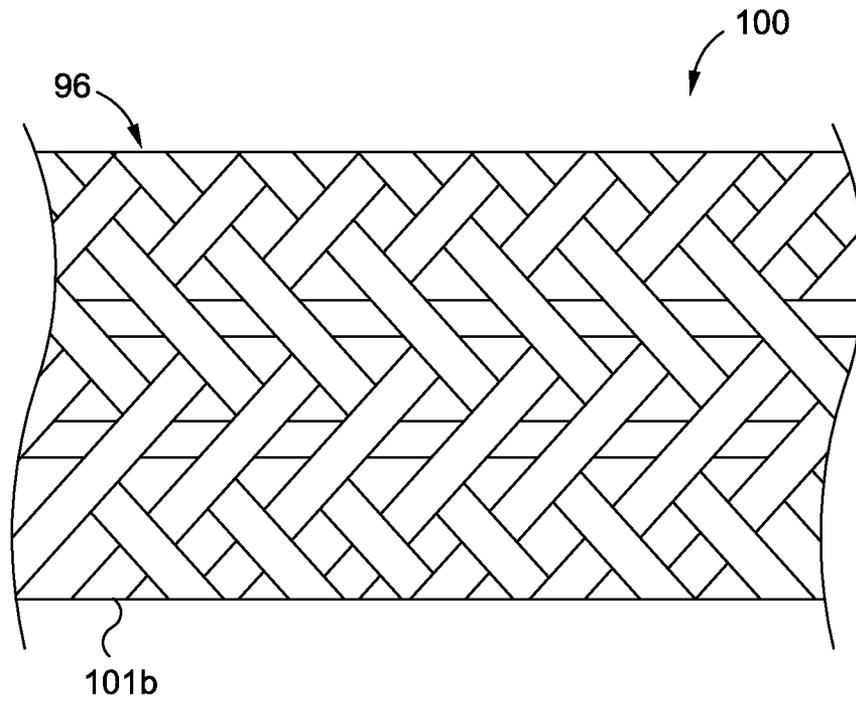


FIG. 5B

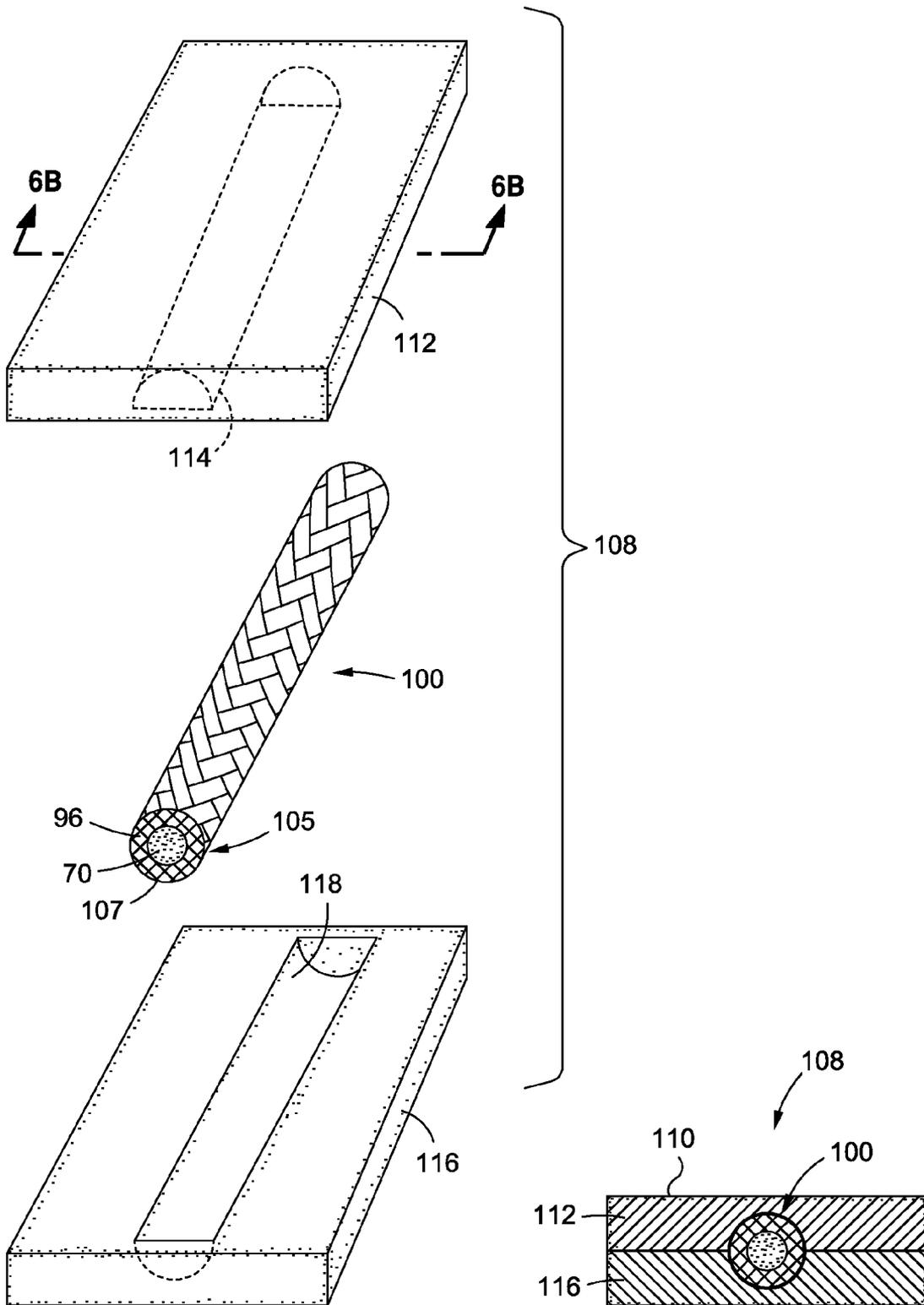


FIG. 6A

FIG. 6B

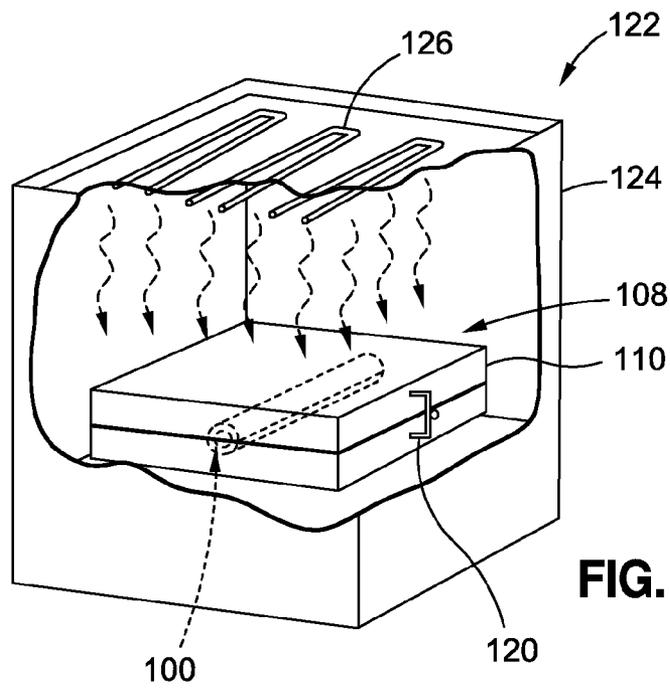


FIG. 7

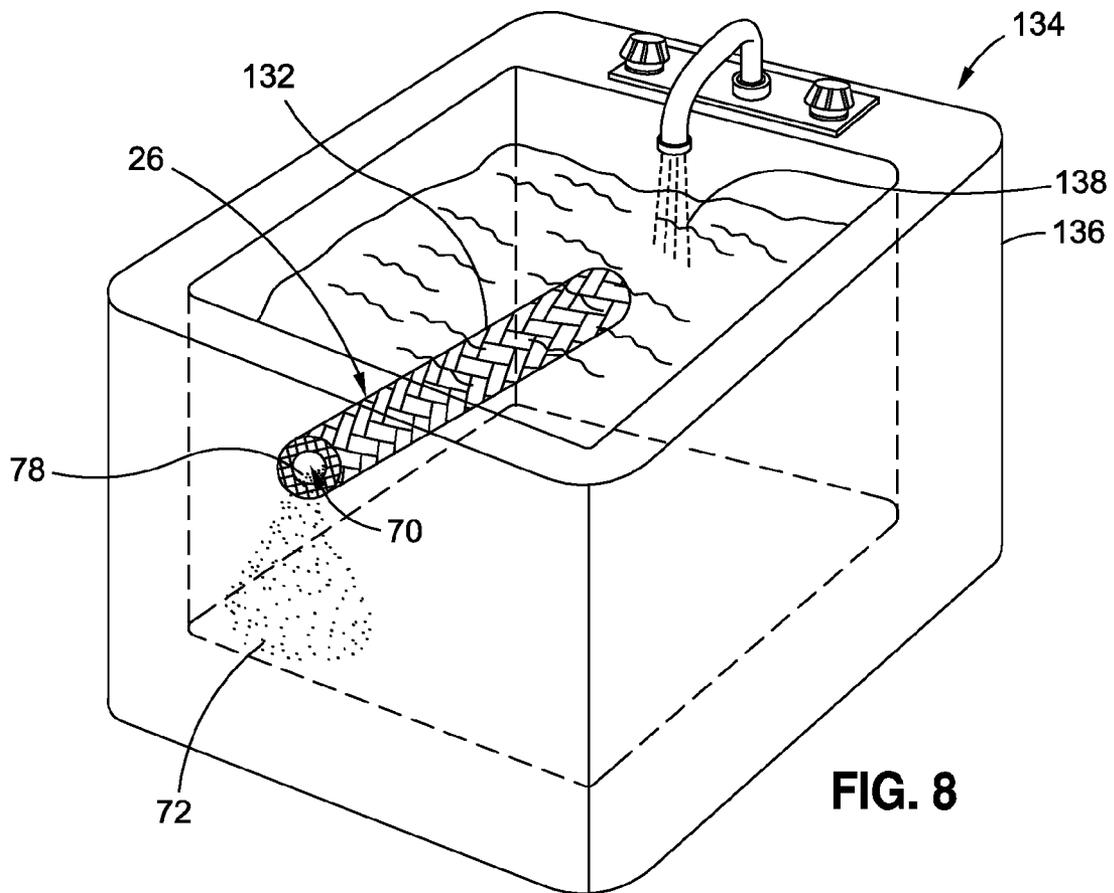


FIG. 8

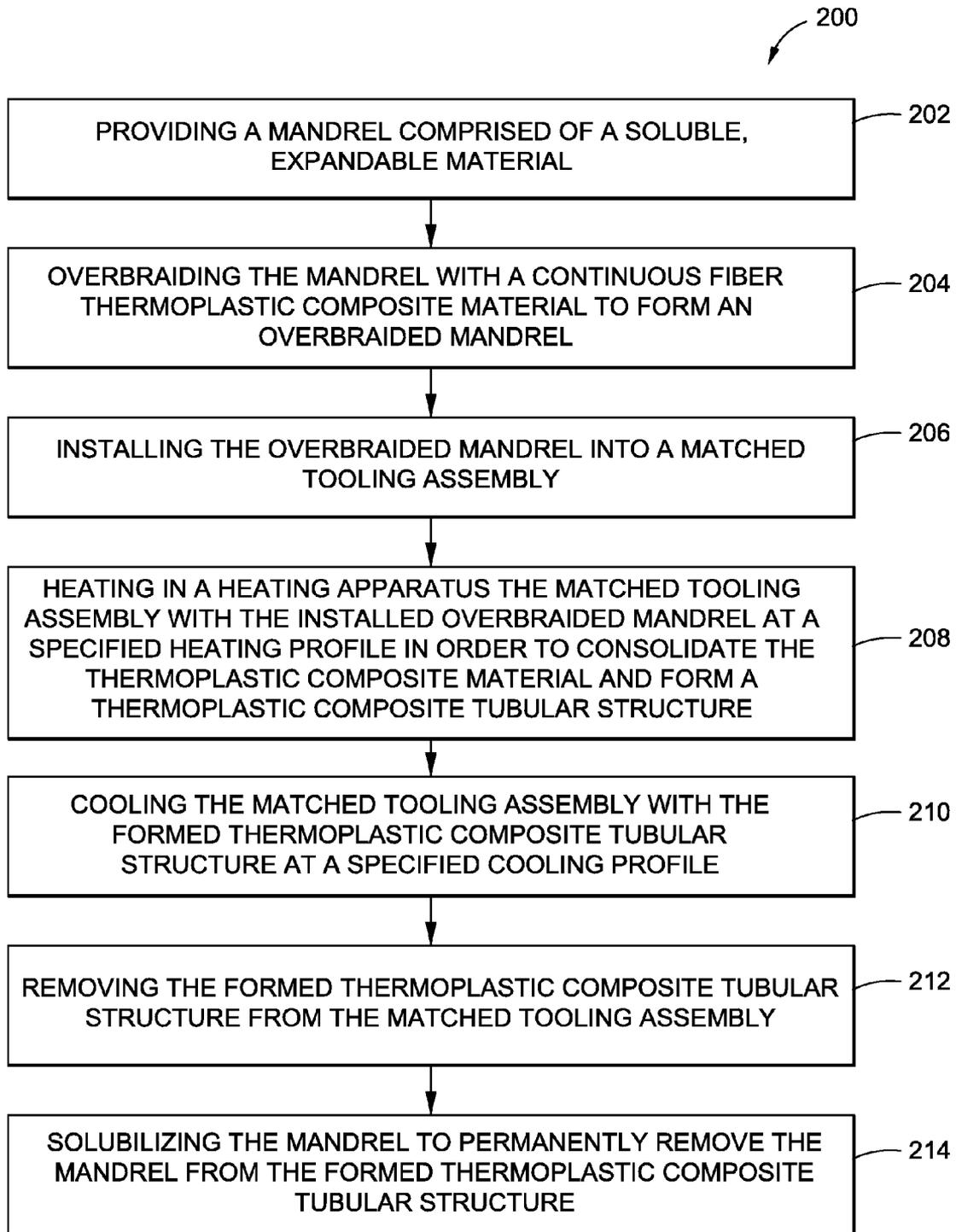


FIG. 9

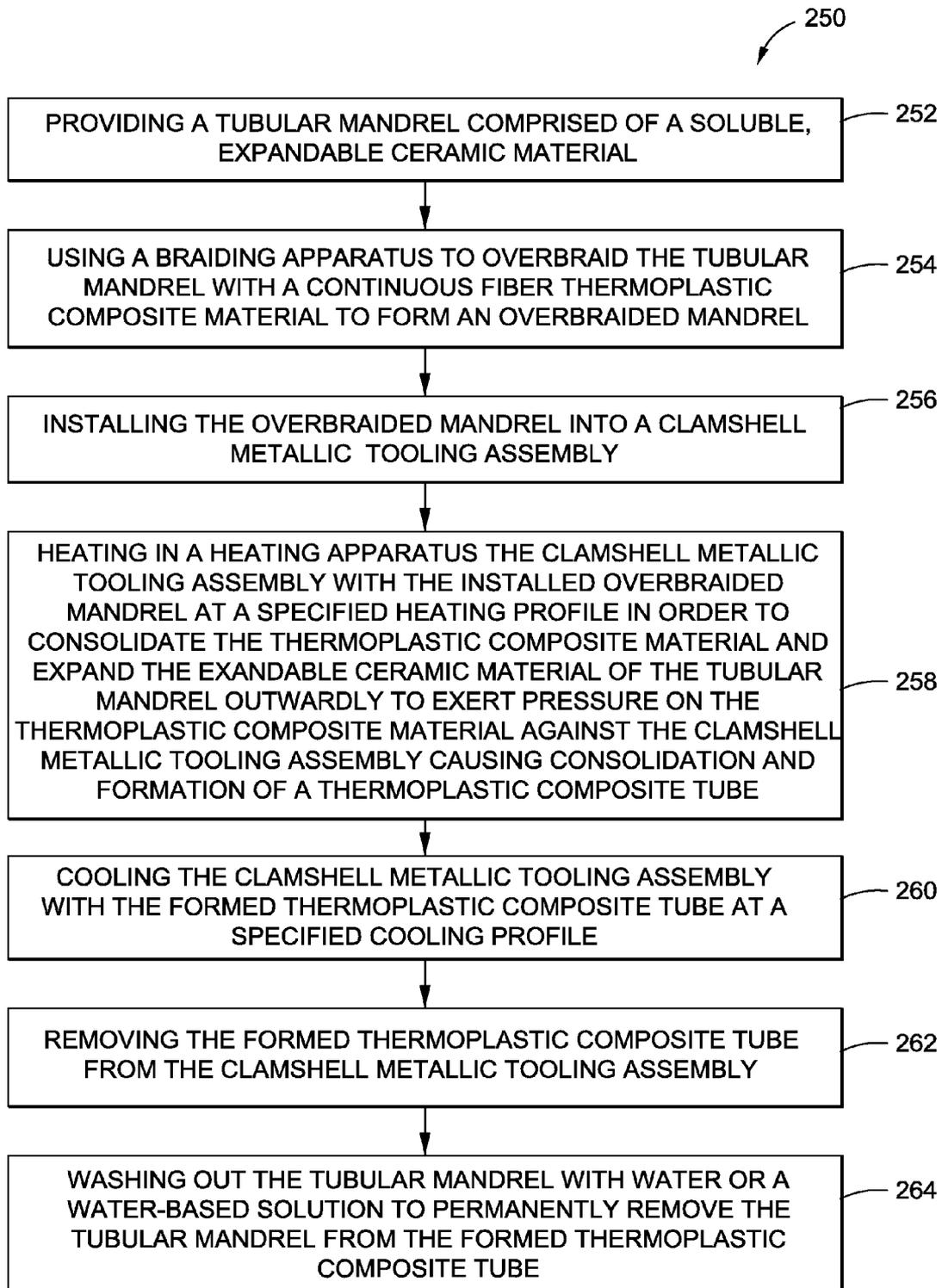


FIG. 10

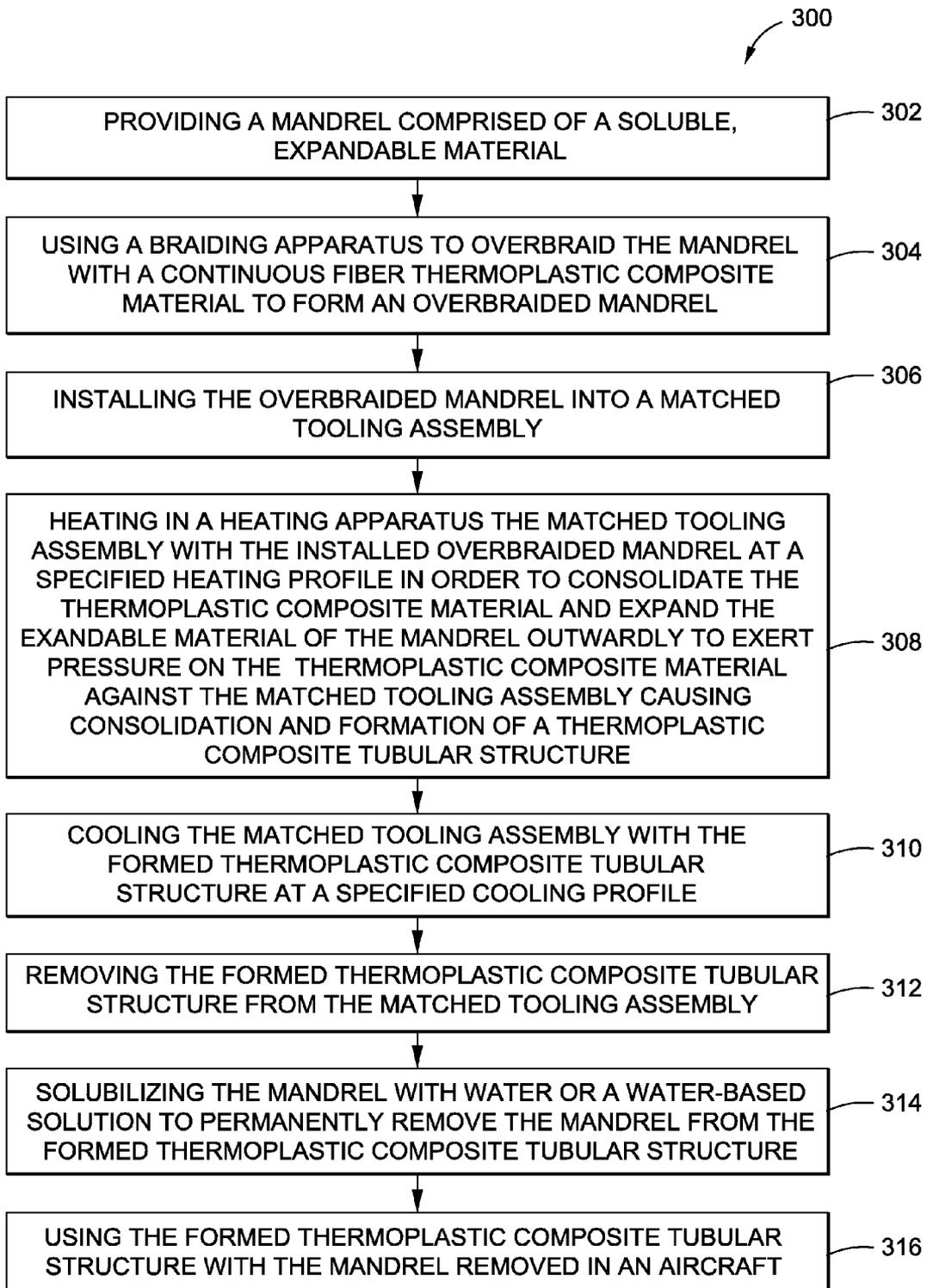


FIG. 11

THERMOPLASTIC COMPOSITE TUBULAR STRUCTURES AND METHODS OF FABRICATING THE SAME

BACKGROUND

1) Field of the Disclosure

The disclosure relates generally to composite structures and methods of fabricating the same, and more particularly, to thermoplastic composite tubular structures and methods of fabricating the same using soluble, expandable tooling.

2) Description of Related Art

Thermoplastic and fiber-reinforced thermoplastic composite structures and parts are used in a wide variety of applications, including in the manufacture of aircraft, spacecraft, rotorcraft, watercraft, automobiles, trucks, and other vehicles and structures, due to their high strength-to-weight ratios, corrosion resistance, and other favorable properties. In aircraft manufacturing and assembly, such thermoplastic and fiber-reinforced thermoplastic composite structures and parts are used in increasing quantities to form the fuselage, wings, tail section, skin panels, and other components.

However, the use of thermoplastic composite materials in the design and manufacture of tubular cylindrical and non-cylindrical structures, such as tubes, pipes, ducts, conduits, and elongate hollow components, for use in aircraft, may be difficult due to tooling removal, processing temperature, outer surface dimensional tolerances, fiber alignment, and other processing challenges. Although known methods exist for fabricating tubular cylindrical and non-cylindrical structures, such known methods may use only resin without fiber reinforcement or may use very small fibers, e.g., millimeters long, that are not continuous, and which may be susceptible to decreased interface properties between the fiber and the matrix. Such decreased interface properties may limit the benefits available from higher strength continuous fibers or may result in thermoplastic composite structures that may be susceptible to fatigue.

In addition, known methods exist for fabricating tubular cylindrical and non-cylindrical structures from thermoset composite materials and from aluminum and titanium metal materials. However, the use of thermoset composite materials may require long cure cycles, e.g., 4 hours to 24 hours or more, due to the crosslinking that the thermoset composite materials undergo, and longer cure cycles may result in increased manufacturing time, and in turn, increased manufacturing costs. Further, the use of metal materials may result in increased weight of the aircraft, which, in turn, may result in increased fuel costs during aircraft flight. Moreover, the use of titanium metal materials may result in increased manufacturing costs due to the high cost of such titanium metal materials.

Accordingly, there is a need in the art for improved thermoplastic composite tubular structures and improved methods for fabricating such thermoplastic composite tubular structures that provide advantages over known structures and methods.

SUMMARY

This need for improved thermoplastic composite tubular structures and improved methods for fabricating such thermoplastic composite tubular structures is satisfied. As discussed in the below detailed description, embodiments of the improved thermoplastic composite tubular structures and improved methods for fabricating such thermoplastic com-

posite tubular structures may provide significant advantages over existing structures and methods.

In an embodiment of the disclosure, there is provided a method of fabricating a thermoplastic composite structure. The method comprises providing a mandrel comprised of a soluble, expandable material. The mandrel has a mandrel cross-section defining a first closed geometric shape. The method further comprises overbraiding the mandrel with a continuous fiber thermoplastic composite material to form an overbraided mandrel. The overbraided mandrel has an overbraided mandrel cross-section defining a second closed geometric shape that corresponds to the first closed geometric shape of the mandrel cross-section. The method further comprises installing the overbraided mandrel into a matched tooling assembly. The method further comprises heating in a heating apparatus the matched tooling assembly with the installed overbraided mandrel at a specified heating profile in order to consolidate the continuous fiber thermoplastic composite material and form a thermoplastic composite tubular structure. The method further comprises cooling the matched tooling assembly with the formed thermoplastic composite tubular structure at a specified cooling profile. The method further comprises removing the formed thermoplastic composite tubular structure from the matched tooling assembly. The method further comprises solubilizing the mandrel to permanently remove the mandrel from the formed thermoplastic composite tubular structure. In another embodiment of the disclosure, there is provided a thermoplastic composite tubular structure formed by this method.

In another embodiment of the disclosure, there is provided a method of fabricating thermoplastic composite tubing. The method comprises providing a tubular mandrel comprised of a soluble, expandable ceramic material. The method further comprises using a braiding apparatus to overbraid the tubular mandrel with a continuous fiber thermoplastic composite material to form an overbraided mandrel. The method further comprises installing the overbraided mandrel into a clamshell metallic tooling assembly. The method further comprises heating in a heating apparatus the clamshell metallic tooling assembly with the installed overbraided mandrel at a specified heating profile in order to consolidate the continuous fiber thermoplastic composite material and expand the expandable ceramic material of the tubular mandrel outwardly to exert pressure on the continuous fiber thermoplastic composite material against the clamshell metallic tooling assembly causing consolidation and formation of a thermoplastic composite tube. The method further comprises cooling the clamshell metallic tooling assembly with the formed thermoplastic composite tube at a specified cooling profile. The method further comprises removing the formed thermoplastic composite tube from the clamshell metallic tooling assembly. The method further comprises washing out the tubular mandrel with water or a water-based solution to permanently remove the tubular mandrel from the formed thermoplastic composite tube. In another embodiment of the disclosure, there is provided a thermoplastic composite tube formed by this method.

In another embodiment of the disclosure, there is provided a method of fabricating an aircraft thermoplastic composite structure. The method comprises providing a mandrel comprised of a soluble, expandable material. The mandrel has a mandrel cross-section defining a first closed geometric shape. The method further comprises using a braiding apparatus to overbraid the mandrel with a continuous fiber thermoplastic composite material to form an overbraided mandrel. The method further comprises installing the overbraided mandrel into a matched tooling assembly. The overbraided mandrel

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has an overbraided mandrel cross-section defining a second closed geometric shape that corresponds to the first closed geometric shape of the mandrel cross-section. The method further comprises heating in a heating apparatus the matched tooling assembly with the installed overbraided mandrel at a specified heating profile in order to consolidate the continuous fiber thermoplastic composite material and expand the expandable material of the mandrel outwardly to exert pressure on the continuous fiber thermoplastic composite material against the matched tooling assembly causing consolidation and formation of a thermoplastic composite tubular structure. The method further comprises cooling the matched tooling assembly with the formed thermoplastic composite tubular structure at a specified cooling profile. The method further comprises removing the formed thermoplastic composite tubular structure from the matched tooling assembly. The method further comprises solubilizing the mandrel with water or a water-based solution to permanently remove the mandrel from the formed thermoplastic composite tubular structure. The method further comprises using the formed thermoplastic composite tubular structure with the mandrel removed in an aircraft. In another embodiment of the disclosure, there is provided an aircraft thermoplastic composite tubular structure fabricated by this method.

The features, functions, and advantages that have been discussed can be achieved independently in various embodiments of the disclosure or may be combined in yet other embodiments further details of which can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosure can be better understood with reference to the following detailed description taken in conjunction with the accompanying drawings which illustrate preferred and exemplary embodiments, but which are not necessarily drawn to scale, wherein:

FIG. 1 is an illustration of a perspective view of an aircraft which may incorporate one or more thermoplastic composite tubular structures fabricated by one of the embodiments of a method of the disclosure;

FIG. 2 is an illustration of a flow diagram of an embodiment of an aircraft manufacturing and service method of the disclosure;

FIG. 3 is an illustration of a functional block diagram of an aircraft;

FIG. 4A is an illustration of a perspective view of one of the embodiments of a mandrel that may be used in method embodiments of the disclosure;

FIG. 4B is an illustration of a cross-sectional view taken along lines 4B-4B of FIG. 4A;

FIG. 4C is an illustration of a perspective view of another one of the embodiments of a mandrel that may be used in method embodiments of the disclosure;

FIG. 4D is an illustration of a cross-sectional view taken along lines 4D-4D of FIG. 4C;

FIG. 4E is an illustration of a cross-sectional view taken along lines 4E-4E of FIG. 4C;

FIG. 5A is an illustration of a schematic top view of a braiding apparatus overbraiding one of the embodiments of a mandrel that may be used in method embodiments of the disclosure;

FIG. 5B is an illustration of a close-up top view of an overbraided mandrel with a triaxial overbraid that may be used in method embodiments of the disclosure;

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FIG. 6A is an illustration of an exploded perspective view of an overbraided mandrel and a matched tooling assembly that may be used in method embodiments of the disclosure;

FIG. 6B is an illustration of a cross-sectional view taken along lines 6B-6B of FIG. 6A;

FIG. 7 is an illustration of a cut-away perspective view of an overbraided mandrel installed in a matched tooling assembly being heated in a heating apparatus that may be used in method embodiments of the disclosure;

FIG. 8 is an illustration of a perspective view of a mandrel being washed out of the formed thermoplastic composite tubular structure in a mandrel removal apparatus that may be used in method embodiments of the disclosure;

FIG. 9 is an illustration of a flow diagram illustrating one of the embodiments of a method of the disclosure;

FIG. 10 is an illustration of a flow diagram illustrating another one of the embodiments of a method of the disclosure; and,

FIG. 11 is an illustration of a flow diagram illustrating another one of the embodiments of a method of the disclosure.

DETAILED DESCRIPTION

Disclosed embodiments will now be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all of the disclosed embodiments are shown. Indeed, several different embodiments may be provided and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete and will fully convey the scope of the disclosure to those skilled in the art.

Now referring to the Figures, FIG. 1 is an illustration of a perspective view of an aircraft 10 that may incorporate one or more thermoplastic composite tubular structures 26, such as an aircraft thermoplastic composite tubular structure 28, fabricated by one of the embodiments of a method 200 (see FIG. 9), a method 250 (see FIG. 10), or a method 300 (see FIG. 11) of the disclosure. As shown in FIG. 1, the aircraft 10 comprises a fuselage 12, a nose 14, a cockpit 16, wings 18 operatively coupled to the fuselage 12, one or more propulsion units 20, a tail vertical stabilizer 22, and one or more tail horizontal stabilizers 24. Although the aircraft 10 shown in FIG. 1 is generally representative of a commercial passenger aircraft, the one or more thermoplastic composite tubular structures 26, as disclosed herein, may also be employed in other types of aircraft or air vehicles. More specifically, the teachings of the disclosed embodiments may be applied to other passenger aircraft, cargo aircraft, military aircraft, rotorcraft, and other types of aircraft or aerial vehicles, as well as aerospace vehicles, satellites, space launch vehicles, rockets, and other aerospace vehicles. It may also be appreciated that embodiments of structures and methods in accordance with the disclosure may be utilized in other transport vehicles, such as boats and other watercraft, trains, automobiles, trucks, buses, or other suitable transport vehicles formed from or utilizing thermoplastic composite tubular structures or parts.

FIG. 2 is an illustration of a flow diagram of an embodiment of an aircraft manufacturing and service method 30 of the disclosure. FIG. 3 is an illustration of a functional block diagram of an aircraft 50. Referring to FIGS. 2-3, embodiments of the disclosure may be described in the context of the aircraft manufacturing and service method 30, as shown in FIG. 2, and the aircraft 50, as shown in FIG. 3. During pre-production, the exemplary aircraft manufacturing and service

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method **30** may include specification and design **32** of the aircraft **50** and material procurement **34**. During production, component and subassembly manufacturing **36** and system integration **38** of the aircraft **50** takes place. Thereafter, the aircraft **50** may go through certification and delivery **40** in order to be placed in service **42**. While in service **42** by a customer, the aircraft **50** is scheduled for routine maintenance and service **44** (which may also include modification, reconfiguration, refurbishment, and so on).

Each of the processes of the aircraft manufacturing and service method **30** may be performed or carried out by a system integrator, a third party, and/or an operator (e.g., a customer). For the purposes of this description, a system integrator may include without limitation any number of aircraft manufacturers and major-system subcontractors; a third party may include without limitation any number of vendors, subcontractors, and suppliers; and an operator may be an airline, leasing company, military entity, service organization, and so on.

As shown in FIG. 3, the aircraft **50** produced by the exemplary aircraft manufacturing and service method **30** may include an airframe **52** with a plurality of high-level systems **54** and an interior **56**. Examples of high-level systems **54** may include one or more of a propulsion system **58**, an electrical system **60**, a hydraulic system **62**, and an environmental system **64**. Any number of other systems may be included. Although an aerospace example is shown, the principles of the invention may be applied to other industries, such as the automotive industry.

Methods and structured embodied herein may be employed during any one or more of the stages of the aircraft manufacturing and service method **30**. For example, components or subassemblies corresponding to component and subassembly manufacturing **36** may be fabricated or manufactured in a manner similar to components or subassemblies produced while the aircraft **50** is in service **42**. Also, one or more apparatus embodiments, method embodiments, or a combination thereof may be utilized during the component and subassembly manufacturing **36** and system integration **38**, for example, by substantially expediting assembly of or reducing the cost of an aircraft **50**. Similarly, one or more of apparatus embodiments, method embodiments, or a combination thereof may be utilized while the aircraft **50** is in service **42**, for example and without limitation, to routine maintenance and service **44**.

In one embodiment of the disclosure, there is provided a method **200** of fabricating a thermoplastic composite tubular structure **26** (see FIGS. 1, 8). FIG. 9 is an illustration of a flow diagram illustrating the method **200** of the disclosure. For purposes of this application, the term "tubular structure" means a structure having a cylindrical or non-cylindrical shape, having a linear or non-linear shape in the lengthwise direction, and having a cross-section defining a closed geometric shape (discussed in detail below). The tubular structure may or may not be hollow or may be partially hollow.

As shown in FIG. 9, the method **200** comprises step **202** of providing a mandrel **70** or tooling (see FIG. 4A) comprised of a soluble, expandable material **72** (see FIGS. 4A, 4C). FIG. 4A is an illustration of a perspective view of one of the embodiments of the mandrel **70**, such as in the form of mandrel **70a**, that may be used in the method **200** (as well as in method **250** (see FIG. 10) and method **300** (see FIG. 11)), of the disclosure. FIG. 4C is an illustration of a perspective view of another one of the embodiments of the mandrel **70b** that may be used in the method **200** of the disclosure. The mandrel **70** may thus, for example, be in the form of mandrel **70a** (see FIG. 4A) or mandrel **70b** (see FIG. 4C), or another suitable

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mandrel form. The mandrel **70** preferably comprises one or more soluble, expandable materials consisting of ceramic, sand, a polymer binder, a soluble organic binder, a soluble inorganic binder, sodium silicate, graphite, one or more additives, and one or more preservatives, or another suitable soluble, expandable material. Preferably, the mandrel material is a high expansion material. Embodiments of the mandrel or tooling that may be used in the disclosed methods include mandrels obtained from Advanced Ceramics Manufacturing, LLC, of Tucson, Ariz., and as disclosed in U.S. Published Patent Application Number 2010/0249303 A1, published Sep. 30, 2012, to Rossfeldt et al. and as disclosed in U.S. Published Patent Application Number 2011/0000398 A1, published Jan. 6, 2011, to Wallen et al., both assigned to Advanced Ceramics Manufacturing, LLC, of Tucson, Ariz., and incorporated herein by reference in their entireties.

Preferably, the mandrel **70** (see FIG. 4A) has a mandrel cross-section **74** (see FIG. 4B) defining a first closed geometric shape **76** (see FIG. 4B). FIG. 4B is an illustration of a cross-sectional view taken along lines 4B-4B of FIG. 4A. As shown in FIG. 4A, the mandrel **70**, such as in the form of mandrel **70a**, may comprise a cylindrical or tubular mandrel **78** having a linear shape **80**. The tubular mandrel **78** has the mandrel cross-section **74** (see FIG. 4B), such as in the form of a mandrel cross-section **74a** (see FIG. 4B), defining the first closed geometric shape **76** (see FIG. 4B), such as a first closed geometric shape **76a** (see FIG. 4B), in the shape of a circle **82**.

As shown in FIG. 4C, the mandrel **70b** comprises a non-cylindrical mandrel **84** having a non-linear shape **86**. FIG. 4D is an illustration of a cross-sectional view taken along lines 4D-4D of FIG. 4C. The non-cylindrical mandrel **84** has the mandrel cross-section **74**, such as in the form of cross-section **74b** (see FIG. 4D), defining the first closed geometric shape **76** at a first end **88** (see FIG. 4C), such as a first closed geometric shape **76b** (see FIG. 4D), in the shape of a square **90** (see FIG. 4D). FIG. 4E is an illustration of a cross-sectional view taken along lines 4E-4E of FIG. 4C. The non-cylindrical mandrel **84** has the mandrel cross-section **74**, such as in the form of cross-section **74c** (see FIG. 4E), defining the first closed geometric shape **76** at a second end **92** (see FIG. 4C), such as a first closed geometric shape **76c** (see FIG. 4E), in the shape of a rectangle **94** (see FIG. 4E).

In addition to the shapes of the circle **82** (see FIG. 4B) and the rectangle **94** (see FIG. 4E), the first closed geometric shape **76** may further include such shapes as a semi-circle, an oval, an ellipse, a parallelogram, a trapezoid, a rhombus, a curvilinear triangle, a crescent, a quadrilateral, a quatrefoil, and polygon shapes, in addition to the square **90** (see FIG. 4D), comprising a triangle, a pentagon, a hexagon, a heptagon, an octagon, a nonagon, a decagon, a hendecagon, a dodecagon, or another suitable closed geometric shape.

As shown in FIG. 9, the method **200** further comprises step **204** of overbraiding the mandrel **70** with a continuous fiber thermoplastic composite material **96** (see FIG. 5A) over an exterior surface **98** (see FIG. 5A) of the mandrel **70**, such as in the form of the tubular mandrel **78**, to form an overbraided mandrel **100** (see FIG. 5A). The use of the continuous fiber thermoplastic composite material **96** allows for preferred configurations or designs of the thermoplastic composite tubular structures **26** to be fabricated due to its ability to form structures in more complicated shapes.

The continuous fiber thermoplastic composite material **96** preferably consists of carbon fiber composite material; carbon fiber reinforced polymer material including carbon fiber reinforced polyphethylene sulfide (PPS), carbon fiber reinforced polyetheretherketone (PEEK), carbon fiber reinforced polyetherketoneketone (PEKK), and carbon fiber reinforced

polyethyleneimine (PEI); nylon, or another suitable thermoplastic composite material. The continuous fiber thermoplastic composite material **96** is preferably in a form consisting of a continuous slit tape thermoplastic composite material, a prepreg unidirectional tape **106** (see FIG. 5A), a prepreg fabric (not shown), a commingled fiber material (not shown), a quasi-isotropic or anisotropic continuous fiber thermoplastic composite material (not shown), or another suitable continuous fiber thermoplastic composite material. Preferably, the continuous fiber thermoplastic composite material **96**, such as in the form of the prepreg unidirectional tape **106**, has a narrow width of $\frac{1}{8}$ inch wide, $\frac{1}{4}$ inch wide, or another suitably narrow width tape. The commingled fiber material may comprise dry fibers with a thermoplastic resin powder embedded in the dry fibers. The continuous fiber thermoplastic composite material **96** may be wound and/or braided around the mandrel in a zero (0) degree direction and also wound or braided in a bias direction. When the continuous fiber thermoplastic composite material **96** is wound or braided in a bias direction, the commingled fiber material may be used so that when the continuous fiber thermoplastic composite material **96** is heated and consolidated, the embedded resin powder fills the dry fibers and melts to result in the consolidated thermoplastic composite tubular structure **26**.

For purposes of this application, "quasi-isotropic continuous fiber thermoplastic composite material" means a laminate that approximates isotropy by orientation of tows in several or more directions in-plane. For example, a quasi-isotropic part may have randomly oriented fibers in all directions or may have fibers oriented such that equal strength is developed all around the plane of the part. In general, a quasi-isotropic laminate made from a prepreg fabric or woven fabric may have tows oriented at 0° (zero degrees), 90° , $+45^\circ$, and -45° , with at least 12.5% of the tows in each of these four directions. Quasi-isotropic properties may also be obtained with braided unidirectional (0 degree) and 60 degree bias oriented tows. For purposes of this application, "anisotropic continuous fiber thermoplastic composite material" means the composite material's directional dependence of a physical property and can be a difference, when measured along different axes, in a material's physical or mechanical properties (absorbance, refractive index, conductivity, tensile strength, etc.). Anisotropic may also be referred to as "unidirectional". The method **200** (as well as method **250** (see FIG. 10) and method **300** (see FIG. 11), provides for fabricating and configuration of highly loaded quasi-isotropic or highly loaded anisotropic (unidirectional) thermoplastic composite continuous fiber tubular structures manufactured with the use of soluble, expandable (high expansion) mandrels or tooling materials.

FIG. 5A is an illustration of a schematic top view of a braiding apparatus **102** for overbraiding one of the embodiments of a mandrel **70** that may be used in method embodiments of the disclosure. As shown in FIG. 5A, the overbraiding of the mandrel **70** is preferably accomplished by using the braiding apparatus **102** having one or more braiding bobbins or tubes **104** for dispensing and braiding the continuous fiber thermoplastic composite material **96** over the mandrel **70**. A braiding apparatus or machine known in the art may be used to overbraid the mandrel. Preferably, the known braiding apparatus or machine has the capability of accommodating changes to the continuous fiber thermoplastic composite material's thickness, gauge, bias angle along the length, cross-sectional shape, cross-sectional angular path along the length, curve, shape of drop, and number of tows. Preferably, the overbraiding of the mandrel **70** is carried out at ambient temperature. The overbraiding process preferably provides for improved damage tolerance and improved fracture tough-

ness properties of the continuous fiber thermoplastic composite material **96** due to the over and under construction of the overbraiding process. In one embodiment, as shown in FIG. 5A, the overbraided mandrel **100** may comprise a continuous fiber thermoplastic composite material **96** with a bias tow only overbraid **101a**.

In another embodiment, as shown in FIG. 5B, the overbraided mandrel **100** may comprise a continuous fiber thermoplastic composite material **96** with a triaxial overbraid **101b**. FIG. 5B is an illustration of a close-up top view of the overbraided mandrel **100** with the triaxial overbraid **101b** that may be used in method embodiments of the disclosure.

The overbraided mandrel **100** preferably has an overbraided mandrel cross-section **105** (see FIG. 6A) defining a second closed geometric shape **107** (see FIG. 6A). Preferably, the second closed geometric shape **107** of the overbraided mandrel cross-section **105** corresponds in shape to the first closed geometric shape **76** of the mandrel cross-section **74** of the mandrel **70**. For example, the second closed geometric shape **17** is in the shape of a larger circle that corresponds to the shape of the circle **82** (see FIG. 4B) of the mandrel cross-section **74a** (see FIG. 4B) of the tubular mandrel **78**. The second closed geometric shape **107** may include such shapes as a circle, a rectangle, a semi-circle, an oval, an ellipse, a parallelogram, a trapezoid, a rhombus, a curvilinear triangle, a crescent, a quadrilateral, a quatrefoil, and polygon shapes, such as a triangle, a square, a pentagon, a hexagon, a heptagon, an octagon, a nonagon, a decagon, a hendecagon, a dodecagon, or another suitable closed geometric shape.

As shown in FIG. 9, the method **200** further comprises step **206** of installing the overbraided mandrel **100** (see FIGS. 6A-6B) into a matched tooling assembly **108** (see FIGS. 6A-6B). FIG. 6A is an illustration of an exploded perspective view of the overbraided mandrel **100** and the matched tooling assembly **108** that may be used in embodiments of the method **200** (as well as in method **250** (see FIG. 10) and method **300** (see FIG. 11)), of the disclosure. FIG. FIG. 6B is an illustration of a cross-sectional view taken along lines 6B-6B of FIG. 6A showing the overbraided mandrel **100** of FIG. 6A installed in the matched tooling assembly **108** of FIG. 6A. The matched tooling assembly **108** preferably comprises a metallic clamshell tooling assembly **110** (see FIG. 6B), such as made from steel, stainless steel, or another suitable metal.

As shown in FIG. 6A, the matched tooling assembly **108** preferably comprises a first portion **112** having a first portion mold side **114** and comprises a second portion **116** having a second portion mold side **118**. The overbraided mandrel **100** may be installed within and between the first portion mold side **114** and the second portion mold side **118**. As shown in FIG. 7, once the matched tooling assembly **108** is closed around the overbraided mandrel **100**, the first portion **112** and the second portion **116** of the matched tooling assembly **108** may be held together via a holding element **120**, such as a clamp or other suitable device.

As shown in FIG. 9, the method **200** further comprises step **208** of heating in a heating apparatus **122** the matched tooling assembly **108** with the installed overbraided mandrel **100** at a specified heating profile in order to consolidate the continuous fiber thermoplastic composite material **96** and form a thermoplastic composite tubular structure **26** (see FIG. 8). FIG. 7 is an illustration of a cut-away perspective view of the overbraided mandrel **100** installed in the matched tooling assembly **108**, such as in the form of the clamshell metallic tooling assembly **110**, being heated in the heating apparatus **122** that may be used in the method **200** (as well as in method **250** (see FIG. 10) and method **300** (see FIG. 11)) of the disclosure.

As shown in FIG. 7, the heating apparatus **122** comprises a convection oven **124** having heating elements **126** that emit heat **128** in order to consolidate the continuous fiber thermoplastic composite material **96**. The method **200** may allow for fabrication of thermoplastic composite tubular structures **26** in a completely out of autoclave fabrication method by applying pressure internally using the expandable material **72** of the mandrel **70**. However, although a convection oven **124** is shown in FIG. 7, the heating apparatus **122** may also consist of an induction oven, an induction heated matched tooling assembly, an autoclave, an integrally heated tooling assembly, or another suitable heating apparatus. Preferably, the specified heating profile comprises a heating temperature in a range of from about 150 degrees Fahrenheit to about 800 degrees Fahrenheit. More preferably, the heating temperature is in a range of from about 400 degrees Fahrenheit to about 750 degrees Fahrenheit. Most preferably, the heating temperature is in a range of from about 550 degrees Fahrenheit to about 700 degrees Fahrenheit. Preferably, the specified heating profile comprises a heating time in a range of from about 5 minutes to about 120 minutes. More preferably, the heating time is in a range of from about 10 minutes to about 60 minutes.

Upon heating in the heating apparatus **122** (see FIG. 7), the expandable material **72** (see FIG. 4A) of the mandrel **70** (see FIG. 4A) preferably expands and exerts pressure on the continuous fiber thermoplastic composite material **96** (see FIG. 5A) against the matched tooling assembly **108** causing consolidation or hardening of the continuous fiber thermoplastic composite material **96** to form the thermoplastic composite tubular structure **26**. As used herein, the terms "consolidate" or "consolidation" mean hardening or toughening of the thermoplastic composite material under heat and/or pressure to form a unitary structure, e.g., thermoplastic composite tubular structure, and cooling of the hardened or toughened unitary structure. Heating methods may include induction, microwave, ultrasonic, resistance, hot jet, laser, autoclave, plasma, or another suitable heating method, and pressurizing techniques may include mold, contact, fiber tension, roller, vacuum bagging or another suitable pressurizing technique. During consolidation, the heat and/or pressure results in flow of resin and wetting of reinforcing fibers of the thermoplastic composite material. Preferably, the pressure exerted by the mandrel on the continuous fiber thermoplastic composite material **96** may be in a range of from about 100 psi (pounds per square inch) to about 400 psi. In addition, by providing a metallic clamshell tooling assembly **110** with smooth, polished surfaces, where pressure is being generated from the inside out, any wrinkles or deformations on the outside of the consolidated or hardened formed thermoplastic composite tubular structure **26** may be avoided or minimized.

As shown in FIG. 9, the method **200** further comprises step **210** of cooling the matched tooling assembly **108** with the formed thermoplastic composite tubular structure **26** at a specified cooling profile. The specified cooling profile preferably comprises a temperature below a glass transition temperature of the continuous fiber thermoplastic composite material **96** forming the overbraided mandrel **100**. As shown in FIG. 9, the method **200** further comprises step **212** of removing the formed thermoplastic composite tubular structure **26** (see FIG. 8) from the matched tooling assembly **108**.

As shown in FIG. 9, the method **200** further comprises step **214** of solubilizing the mandrel **70** to permanently remove the mandrel **70** from the formed thermoplastic composite tubular structure **26**. FIG. 8 is an illustration of a perspective view of the mandrel **70** being washed out of the formed thermoplastic composite tubular structure **26** in a mandrel removal apparatus **134** that may be used in the method **200** (as well as in method **250** (see FIG. 10) and method **300** (see FIG. 11)) of the disclosure. As shown in FIG. 8, the mandrel removal apparatus **134** may comprise a washing vessel **136**, such as a sink, that dispenses water **138** or another water-based solution to wash out and to permanently remove the mandrel **70**, such as in the form of the tubular mandrel **78**, from the formed thermoplastic composite tubular structure **26**, such as in the form of a thermoplastic composite tube **132**. Solubilizing the mandrel **70** thus further comprises solubilizing the mandrel **70** with water **138** or a water-based solution to permanently remove the mandrel **70** from the formed thermoplastic composite tubular structure **26**. The mandrel **70** may be solubilized and washed out of the formed thermoplastic composite tubular structure **26** in pieces or portions of the soluble, expandable material **72** that forms the mandrel **70**. The removed mandrel **70** or soluble, expandable material **72** may be discarded or recycled. In another embodiment of the disclosure, there is provided a thermoplastic composite tubular structure **26** (see FIG. 8) fabricated by the method **200** discussed above. The thermoplastic composite tubular structure **26** may comprise a thermoplastic composite tube **132** (see FIG. 8), a pipe, a duct, an elongate hollow structure, or another suitable thermoplastic composite tubular structure **26**, and may be cylindrical or non-cylindrical and may be linear or non-linear.

In another embodiment of the disclosure, there is provided a method **250** of fabricating thermoplastic composite tubing **132** (see FIG. 8). FIG. 10 is an illustration of a flow diagram illustrating the method **250** of the disclosure. As shown in FIG. 10, the method **250** comprises step **252** of providing a tubular mandrel **78** (see FIG. 4A) comprised of a soluble, expandable ceramic material **72** (see FIG. 4A). The tubular mandrel **78** preferably comprises one or more soluble, expandable materials consisting of ceramic, sand, a polymer binder, a soluble organic binder, a soluble inorganic binder, sodium silicate, graphite, one or more additives, and one or more preservatives, or another suitable soluble, expandable material.

As shown in FIG. 10, the method **250** further comprises step **254** of using a braiding apparatus **102** (see FIG. 5A) to overbraid the tubular mandrel **78** (see FIG. 4A) with a continuous fiber thermoplastic composite material **96** (see FIG. 5A) to form an overbraided mandrel **100** (see FIG. 5A). As discussed above, the continuous fiber thermoplastic composite material **96** preferably consists of carbon fiber composite material; carbon fiber reinforced polymer material including carbon fiber reinforced polyphenylene sulfide (PPS), carbon fiber reinforced polyetheretherketone (PEEK), carbon fiber reinforced polyetheretherketoneketone (PEKK), and carbon fiber reinforced polyethyleneimine (PEI); nylon, or another suitable thermoplastic composite material. As shown in FIG. 5A, the braiding apparatus **102** has one or more braiding bobbins or tubes **104** for dispensing and braiding the continuous fiber thermoplastic composite material **96** over the tubular mandrel **78**. The continuous fiber thermoplastic composite material **96** preferably consists of a continuous slit tape thermoplastic composite material, a prepreg unidirectional tape **106** (see FIG. 5A), a prepreg fabric (not shown), a commingled fiber material (not shown), a quasi-isotropic or anisotropic continuous fiber thermoplastic composite material (not shown), or another suitable continuous fiber thermoplastic composite material.

As shown in FIG. 10, the method **250** further comprises step **256** of installing the overbraided mandrel **100** (see FIG. 6B) into a clamshell metallic tooling assembly **110** (see FIG. 6B). As shown in FIG. 6B, the clamshell metallic tooling

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assembly **110** preferably comprises the first portion **112** and the second portion **116** that may be held together around the overbraided mandrel **100** via the holding element **120**, such as a clamp or other suitable device.

As shown in FIG. **10**, the method **250** further comprises step **258** of heating in the heating apparatus **122** (see FIG. **7**) the clamshell metallic tooling assembly **110** (see FIG. **7**) with the installed overbraided mandrel **100** (see FIG. **7**) at a specified heating profile in order to consolidate the continuous fiber thermoplastic composite material **96** (see FIG. **5A**). Upon heating, the expandable ceramic material of the tubular mandrel **78** (see FIG. **4A**) expands outwardly to exert pressure on the continuous fiber thermoplastic composite material **96** against the clamshell metallic tooling assembly **110** causing consolidation and formation of a thermoplastic composite tube **132** (see FIG. **8**).

As shown in FIG. **7**, the overbraided mandrel **100** installed in the clamshell metallic tooling assembly **110** is being heated in the heating apparatus **122** that may be used in the method **250** of the disclosure. As shown in FIG. **7** and discussed above, the heating apparatus **122** may comprise the convection oven **124** having heating elements **126** that emit heat **128** in order to consolidate the continuous fiber thermoplastic composite material **96**. Although the convection oven **124** is shown in FIG. **7**, the heating apparatus **122** may also preferably consist of an autoclave, an induction oven, an induction heated matched tooling assembly, an integrally heated tooling assembly, or another suitable heating apparatus. Preferably, the specified heating profile comprises a heating temperature in a range of from about 150 degrees Fahrenheit to about 800 degrees Fahrenheit. More preferably, the heating temperature is in a range of from about 400 degrees Fahrenheit to about 750 degrees Fahrenheit. Most preferably, the heating temperature is in a range of from about 550 degrees Fahrenheit to about 700 degrees Fahrenheit. Preferably, the specified heating profile comprises a heating time in a range of from about 5 minutes to about 120 minutes. More preferably, the heating time is in a range of from about 10 minutes to about 60 minutes.

As shown in FIG. **10**, the method **250** further comprises step **260** of cooling the clamshell metallic tooling assembly **110** with the formed thermoplastic composite tube **132** (see FIG. **8**) at a specified cooling profile. As discussed above, the specified cooling profile preferably comprises a temperature below a glass transition temperature of the continuous fiber thermoplastic composite material **96** (see FIG. **5A**) forming the overbraided mandrel **100** (see FIG. **5A**). As shown in FIG. **10**, the method **250** further comprises step **262** of removing the formed thermoplastic composite tube **132** (see FIG. **8**) from the clamshell metallic tooling assembly **110** (see FIG. **7**).

As shown in FIG. **10**, the method **250** further comprises step **264** of washing out the tubular mandrel **78** (see FIG. **8**) with water **138** (see FIG. **8**) or a water-based solution to permanently remove the tubular mandrel **78** from the formed thermoplastic composite tube **132** (see FIG. **8**). The removed tubular mandrel **78** or soluble, expandable material **72** may be discarded or recycled. In another embodiment of the disclosure, there is provided a thermoplastic composite tube **132** (see FIG. **8**) formed by the method **250** discussed above. The thermoplastic composite tube **132** may be linear or non-linear.

In another embodiment of the disclosure, there is provided a method **300** of fabricating an aircraft thermoplastic composite tubular structure **28** (see FIG. **1**). FIG. **11** is an illustration of a flow diagram illustrating the method **300** of the disclosure. The method **300** comprises step **302** of providing

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a mandrel **70** (see FIG. **4A**) comprised of a soluble, expandable material **72** (see FIG. **4A**). The mandrel **70** may, for example, be in the form of mandrel **70a** (see FIG. **4A**) or mandrel **70b** (see FIG. **4C**), or another suitable mandrel form. The mandrel **70** preferably comprises one or more soluble, expandable materials consisting of ceramic, sand, a polymer binder, a soluble organic binder, a soluble inorganic binder, sodium silicate, graphite, one or more additives, and one or more preservatives, or another suitable soluble, expandable material.

As discussed above, preferably, the mandrel **70** has the mandrel cross-section **74** (see FIG. **4B**) defining the first closed geometric shape **76** (see FIG. **4B**). In addition to the shapes of the circle **82** (see FIG. **4B**) and the rectangle **94** (see FIG. **4E**), the first closed geometric shape **76** may further include such shapes as a semi-circle, an oval, an ellipse, a parallelogram, a trapezoid, a rhombus, a curvilinear triangle, a crescent, a quadrilateral, a quatrefoil, and polygon shapes, in addition to the square **90**, comprising a triangle, a pentagon, a hexagon, a heptagon, an octagon, a nonagon, a decagon, a hendecagon, a dodecagon, or another suitable closed geometric shape.

As shown in FIG. **11**, the method **300** further comprises step **304** of using the braiding apparatus **102** (see FIG. **5A**) to overbraid the mandrel **70** with the continuous fiber thermoplastic composite material **96** (see FIG. **5A**) to form the overbraided mandrel **100** (see FIG. **5A**). As discussed above, the continuous fiber thermoplastic composite material **96** preferably consists of carbon fiber composite material; carbon fiber reinforced polymer material including carbon fiber reinforced polyphethylene sulfide (PPS), carbon fiber reinforced polyetheretherketone (PEEK), carbon fiber reinforced polyetherketoneketone (PEKK), and carbon fiber reinforced polyethyleneimine (PEI); nylon, or another suitable thermoplastic composite material. The continuous fiber thermoplastic composite material **96** preferably consists of a continuous slit tape thermoplastic composite material, a prepreg unidirectional tape **106** (see FIG. **5A**), a prepreg fabric (not shown), a commingled fiber material (not shown), a quasi-isotropic or anisotropic continuous fiber thermoplastic composite material (not shown), or another suitable continuous fiber thermoplastic composite material.

The overbraided mandrel **100** preferably has the overbraided mandrel cross-section **105** (see FIG. **6A**) defining the second closed geometric shape **107** (see FIG. **6A**). As discussed above, preferably, the second closed geometric shape **107** of the overbraided mandrel cross-section **105** corresponds in shape to the first closed geometric shape **76** of the mandrel cross-section **74** of the mandrel **70**. The second closed geometric shape **107** may include such shapes as a circle, a rectangle, a semi-circle, an oval, an ellipse, a parallelogram, a trapezoid, a rhombus, a curvilinear triangle, a crescent, a quadrilateral, a quatrefoil, and polygon shapes, such as a triangle, a square, a pentagon, a hexagon, a heptagon, an octagon, a nonagon, a decagon, a hendecagon, a dodecagon, or another suitable closed geometric shape.

As shown in FIG. **11**, the method **300** further comprises step **306** of installing the overbraided mandrel **100** (see FIG. **6B**) into the matched tooling assembly **108** (see FIG. **6B**). The matched tooling assembly **108** preferably comprises a metallic clamshell tooling assembly **110** (see FIG. **6B**). As shown in FIG. **6B**, once the matched tooling assembly **108** is closed around the overbraided mandrel **100**, the first portion **112** and the second portion **116** of the matched tooling assembly **108** may be held together via a holding element **120**, such as a clamp or other suitable device.

As shown in FIG. 11, the method 300 further comprises step 308 of heating in the heating apparatus 122 (see FIG. 7) the matched tooling assembly 108 (see FIG. 7) with the installed overbraided mandrel 100 (see FIG. 7) at a specified heating profile in order to consolidate the continuous fiber thermoplastic composite material 96 (see FIG. 5A). Upon heating in the heating apparatus 122 (see FIG. 7), the expandable material 72 (see FIG. 4A) of the mandrel 70 (see FIG. 4A) preferably expands and exerts a pressure on the continuous fiber thermoplastic composite material 96 (see FIG. 5A) against the matched tooling assembly 108 causing consolidation or hardening of the continuous fiber thermoplastic composite material 96.

As discussed above, the heating apparatus 122 may comprise a convection oven 124 (see FIG. 7) having heating elements 126 that emit heat 128 in order to consolidate the continuous fiber thermoplastic composite material 96, or the heating apparatus 122 may also comprise an autoclave, an induction oven, an induction heated matched tooling assembly, an integrally heated tooling assembly, or another suitable heating apparatus. Preferably, the specified heating profile comprises a heating temperature in a range of from about 150 degrees Fahrenheit to about 800 degrees Fahrenheit. More preferably, the heating temperature is in a range of from about 400 degrees Fahrenheit to about 750 degrees Fahrenheit. Most preferably, the heating temperature is in a range of from about 550 degrees Fahrenheit to about 700 degrees Fahrenheit. Preferably, the specified heating profile comprises a heating time in a range of from about 5 minutes to about 120 minutes. More preferably, the heating time is in a range of from about 10 minutes to about 60 minutes.

As shown in FIG. 11, the method 300 further comprises step 310 of cooling the matched tooling assembly 108 with the formed thermoplastic composite tubular structure 26 at a specified cooling profile. The specified cooling profile preferably comprises a temperature below a glass transition temperature of the continuous fiber thermoplastic composite material 96 forming the overbraided mandrel 100. As shown in FIG. 11, the method 300 further comprises step 312 of removing the formed thermoplastic composite tubular structure 26 from the matched tooling assembly 108 (see FIG. 7).

As shown in FIG. 11, the method 300 further comprises step 314 of solubilizing the mandrel 70 (see FIG. 8) with water 138 (see FIG. 8) or a water-based solution to permanently remove the mandrel 70 from the formed thermoplastic composite tubular structure 26 (see FIG. 8). As shown in FIG. 11, the method 300 further comprises using the formed thermoplastic composite tubular structure 26 with the mandrel 70 removed in an aircraft 10 (see FIG. 1). The removed mandrel 70 or soluble, expandable material 72 may be discarded or recycled. In another embodiment of the disclosure, there is provided an aircraft thermoplastic composite tubular structure 28 (see FIG. 1) formed by the method 300 discussed above. The aircraft thermoplastic composite tubular structure 28 may comprise a thermoplastic composite tube 132 (see FIG. 8), a pipe, a duct, an elongate hollow structure, or another suitable aircraft thermoplastic composite tubular structure 26, and may be cylindrical or non-cylindrical and may be linear or non-linear.

Disclosed embodiments of the method 200, method 250, method 300, thermoplastic composite tubular structure 26, and thermoplastic composite tube 132 may, as compared to existing methods and structures, provide decreased manufacturing time and decreased material costs, which, in turn, may result in decreased overall manufacturing costs; provide for decreased weight of the aircraft, which, in turn, may result in decreased fuel costs during aircraft flight and improved

weight competitiveness; alleviate or mitigate corrosion and electromagnetic issues of known metal materials; and provide thermoplastic composite tubular structures with high strength, high performance, improved fracture toughness properties, and improved damage tolerance. Further, disclosed embodiments of the method 200, method 250, method 300, thermoplastic composite tubular structure 26, and thermoplastic composite tube 132 provide for the rapid fabrication of highly loaded thermoplastic composite quasi-isotropic or anisotropic continuous fiber tubular shapes using soluble, high expansion mandrels or tooling, and provide for the rapid fabrication of continuous fiber thermoplastic composite tubular structures, in particular, with high performance, high strength, thermoplastic composite materials, such as PEEK and PEKK. This allows for fabrication of thermoplastic composite tubular structure 26 in a completely out of autoclave fabrication method by applying pressure internally using the expandable material of the mandrel or tooling. Additionally, the mandrel is soluble and may be permanently removed by simply washing out the mandrel or tooling with water or water based solutions.

Many modifications and other embodiments of the disclosure will come to mind to one skilled in the art to which this disclosure pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. The embodiments described herein are meant to be illustrative and are not intended to be limiting or exhaustive. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

What is claimed is:

1. A method of fabricating a thermoplastic composite tubular structure, the method comprising:
 - using a braiding apparatus to overbraid a single mandrel with a continuous fiber thermoplastic composite material to form an overbraided mandrel, the mandrel comprising a soluble, expandable material, the continuous fiber thermoplastic composite material consisting of a continuous slit tape thermoplastic composite material, and having a mandrel cross-section defining a first closed geometric shape, and the overbraided mandrel having an overbraided mandrel cross-section defining a second closed geometric shape that corresponds to the first closed geometric shape of the mandrel cross-section;
 - installing the overbraided mandrel into a metallic clamshell tooling assembly;
 - heating in a heating apparatus the metallic clamshell tooling assembly with the installed overbraided mandrel at a specified heating profile, and generating pressure from inside the installed overbraided mandrel out to the metallic clamshell tooling assembly, in order to consolidate the continuous fiber thermoplastic composite material and form a thermoplastic composite tubular structure, wherein the heating apparatus is selected from the group consisting of a convection oven, an induction oven, an autoclave, and an integrally heated tooling assembly, and wherein the pressure is in a range of from about 100 psi (pounds per square inch) to about 400 psi;
 - cooling the metallic clamshell tooling assembly with the formed thermoplastic composite tubular structure at a specified cooling profile;
 - removing the formed thermoplastic composite tubular structure from the metallic clamshell tooling assembly; and

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solubilizing the mandrel to permanently remove the mandrel from the formed thermoplastic composite tubular structure.

2. The method of claim 1 wherein the soluble, expandable material of the mandrel is selected from the group consisting of one or more of ceramic, sand, a polymer binder, a soluble organic binder, a soluble inorganic binder, sodium silicate, graphite, one or more additives, and one or more preservatives.

3. The method of claim 1 wherein the first closed geometric shape and the corresponding second closed geometric shape are each selected from the group consisting of a circle, a semi-circle, a rectangle, an oval, an ellipse, a parallelogram, a trapezoid, a rhombus, a curvilinear triangle, a crescent, a quadrilateral, a quatrefoil, and a polygon comprising a triangle, a square, a pentagon, a hexagon, a heptagon, an octagon, a nonagon, a decagon, a hendecagon, and a dodecagon.

4. The method of claim 1 wherein the continuous fiber thermoplastic composite material is a material selected from the group consisting of carbon fiber composite material; carbon fiber reinforced polymer material including carbon fiber reinforced polyphenylene sulfide (PPS), carbon fiber reinforced polyetheretherketone (PEEK), carbon fiber reinforced polyetherketoneketone (PEKK), and carbon fiber reinforced polyethyleneimine (PEI); and nylon.

5. The method of claim 1 wherein the specified heating profile comprises a heating temperature in a range of from about 150 degrees Fahrenheit to about 800 degrees Fahrenheit and a heating time in a range of from about 5 minutes to about 120 minutes.

6. The method of claim 1 wherein upon heating in the heating apparatus, the expandable material of the mandrel expands and exerts pressure on the continuous fiber thermoplastic composite material against the metallic clamshell tooling assembly causing consolidation of the continuous fiber thermoplastic composite material.

7. The method of claim 1 wherein the specified cooling profile comprises a temperature below a glass transition temperature of the thermoplastic composite material forming the overbraided mandrel.

8. The method of claim 1 wherein solubilizing the mandrel further comprises solubilizing the mandrel with water or a water-based solution to permanently remove the mandrel from the formed thermoplastic composite tubular structure.

9. A method of fabricating thermoplastic composite tubing, the method comprising:

using a braiding apparatus to overbraid a single tubular mandrel with a continuous fiber thermoplastic composite material to form an overbraided mandrel, the tubular mandrel comprising a soluble, expandable ceramic material, the continuous fiber thermoplastic composite material consisting of a continuous slit tape thermoplastic composite material;

installing the overbraided mandrel into a clamshell metallic tooling assembly;

heating in a heating apparatus the clamshell metallic tooling assembly with the installed overbraided mandrel at a specified heating profile in order to consolidate the continuous fiber thermoplastic composite material and expand the expandable ceramic material of the tubular mandrel outwardly to exert pressure on the continuous fiber thermoplastic composite material against the clamshell metallic tooling assembly causing consolidation and formation of a thermoplastic composite tube, and wherein the pressure is in a range of from about 100 psi (pounds per square inch) to about 400 psi, wherein the heating apparatus is selected from the group consisting

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of a convection oven, an induction oven, an autoclave, and an integrally heated tooling assembly; cooling the clamshell metallic tooling assembly with the formed thermoplastic composite tube at a specified cooling profile;

removing the formed thermoplastic composite tube from the clamshell metallic tooling assembly; and, washing out the tubular mandrel with water or a water-based solution to permanently remove the tubular mandrel from the formed thermoplastic composite tube.

10. The method of claim 9 wherein the continuous fiber thermoplastic composite material is a material selected from the group consisting of carbon fiber composite material; carbon fiber reinforced polymer material including carbon fiber reinforced polyphenylene sulfide (PPS), carbon fiber reinforced polyetheretherketone (PEEK), carbon fiber reinforced polyetherketoneketone (PEKK), and carbon fiber reinforced polyethyleneimine (PEI); and nylon.

11. The method of claim 9 wherein the specified heating profile comprises a heating temperature in a range of from about 150 degrees Fahrenheit to about 800 degrees Fahrenheit and a heating time in a range of from about 5 minutes to about 120 minutes.

12. A method of fabricating an aircraft thermoplastic composite tubular structure, the method comprising:

providing a mandrel comprised of a soluble, expandable material, the mandrel having a mandrel cross-section defining a first closed geometric shape;

using a braiding apparatus to overbraid a single mandrel with a continuous fiber thermoplastic composite material to form an overbraided mandrel, the mandrel comprising a soluble, expandable material and having a mandrel cross-section defining a first closed geometric shape, the continuous fiber thermoplastic composite material consisting of a continuous slit tape thermoplastic composite material;

the overbraided mandrel having an overbraided mandrel cross-section defining a second closed geometric shape that corresponds to the first closed geometric shape of the mandrel cross-section;

installing the overbraided mandrel into a metallic clamshell tooling assembly;

heating in a heating apparatus the metallic clamshell tooling assembly with the installed overbraided mandrel at a specified heating profile in order to consolidate the continuous fiber thermoplastic composite material and expand the expandable material of the mandrel outwardly to exert pressure on the continuous fiber thermoplastic composite material against the metallic clamshell tooling assembly causing consolidation and formation of a thermoplastic composite tubular structure, and wherein the pressure is in a range of from about 100 psi (pounds per square inch) to about 400 psi, wherein the heating apparatus is selected from the group consisting of a convection oven, an induction oven, an autoclave, and an integrally heated tooling assembly;

cooling the metallic clamshell tooling assembly with the formed thermoplastic composite structure at a specified cooling profile;

removing the formed thermoplastic composite tubular structure from the metallic clamshell tooling assembly; solubilizing the mandrel with water or a water-based solution to permanently remove the mandrel from the formed thermoplastic composite tubular structure; and, using the formed thermoplastic composite tubular structure with the mandrel removed in an aircraft.

13. The method of claim 12 wherein the soluble, expand-
able material of the mandrel is selected from the group con-
sisting of one or more of ceramic, sand, a polymer binder, a
soluble organic binder, a soluble inorganic binder, sodium
silicate, graphite, one or more additives, and one or more
preservatives. 5

14. The method of claim 12 wherein the continuous fiber
thermoplastic composite material is a material selected from
the group consisting of carbon fiber composite material; car-
bon fiber reinforced polymer material including carbon fiber
reinforced polyphenylene sulfide (PPS), carbon fiber rein-
forced polyetheretherketone (PEEK), carbon fiber reinforced
polyetherketoneketone (PEKK), and carbon fiber reinforced
polyethyleneimine (PEI); and nylon. 10

15. The method of claim 12 wherein the specified heating
profile comprises a heating temperature in a range of from
about 150 degrees Fahrenheit to about 800 degrees Fahren-
heit and a heating time in a range of from about 5 minutes to
about 120 minutes. 15

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